Peak-Seeking Optimization of Trim for Reduced Fuel Consumption

Flight-Test Results

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Outline

Introduction

- US domestic flights in 2011:
  - 12.1 billion gallons of fuel
  - 114.6 million metric tons of CO_2 equivalent
- NASA Environmentally Responsible Aviation project
  - Mitigate impacts of aviation on the environment
  - Reduce fuel consumption and emissions

State-of-the-art

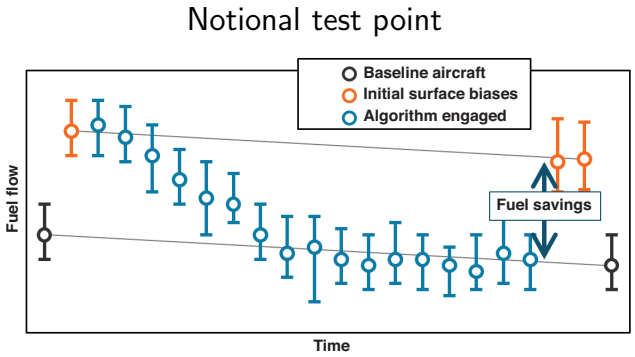
- Airplanes use scheduled trim solutions
- Trim designed a priori with
  - Models
  - Wind-tunnels
  - Flight-test data
- Scheduled trim solutions may not address:
  - Operating in off-nominal flight conditions
  - Subtle manufacturing differences compared to aircraft of the same type
  - Modifications such as winglets, external stores, blisters, engine upgrades, or repairs to damage
  - Increased flexibility with age, leading to a different wing shape under load

Real-time trim optimization

Concept

Use real-time performance measurements to tune trim setting

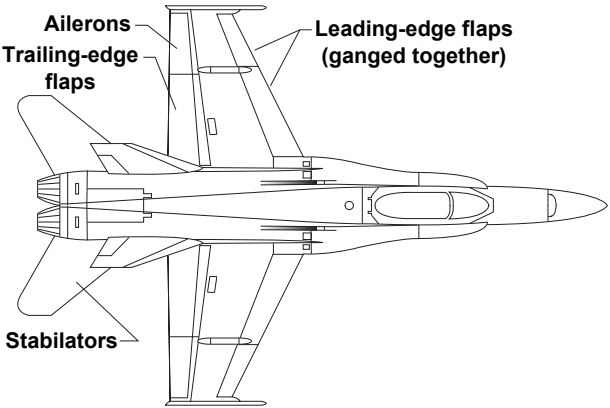
- Small but meaningful fuel savings possible
- Noisy measurements are challenging
- Multiple effectors



Previous research

Modified F/A-18, tail number 853

- Primarily a flight controls research platform
- Heavily instrumented, including fuel flow meters
  - Production fuel flow meters
  - Research-grade fuel flow meters
- Experiment software has full authority over surfaces & throttles
- Reverts to production control system if a constraint is violated

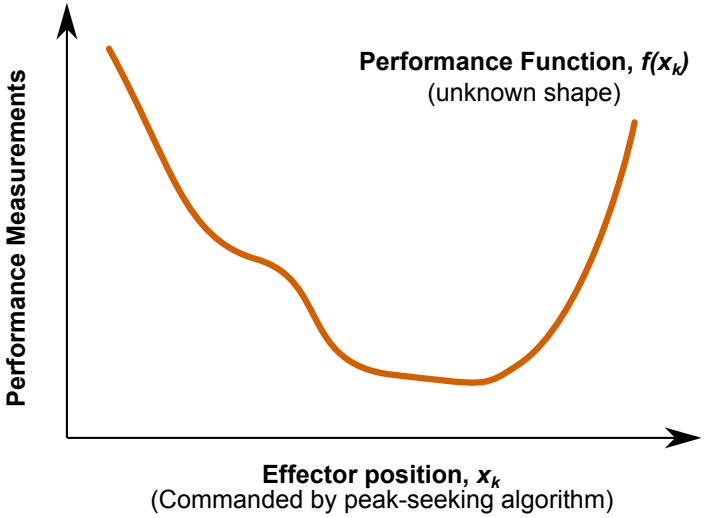


Research control law

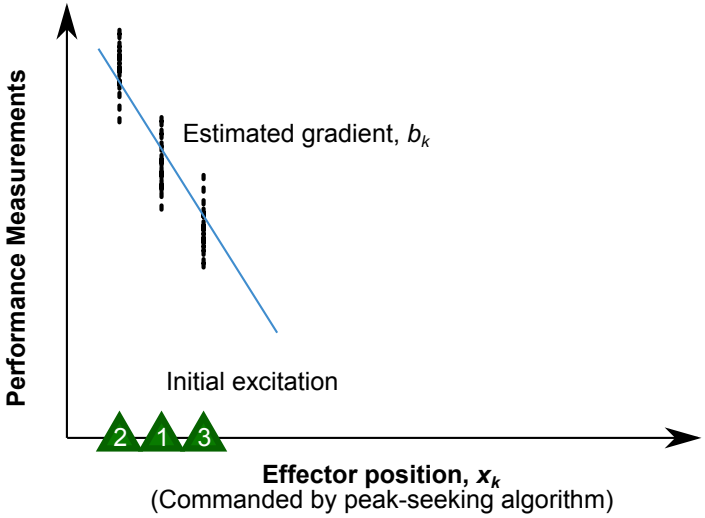
- Inner loop: Non-linear dynamic inversion (Miller)
- Research autopilots
  - Altitude hold
  - Airspeed hold
  - Wing leveler

Peak-seeking algorithm, simplified example

Peak-seeking algorithm, simplified example



Peak-seeking algorithm, simplified example



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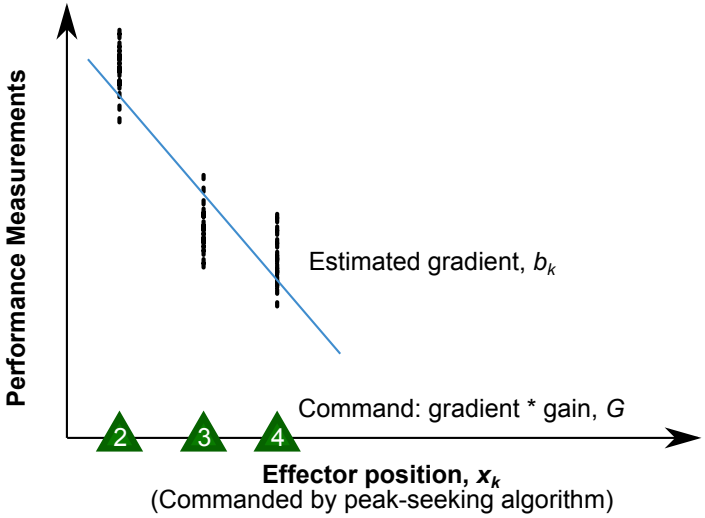

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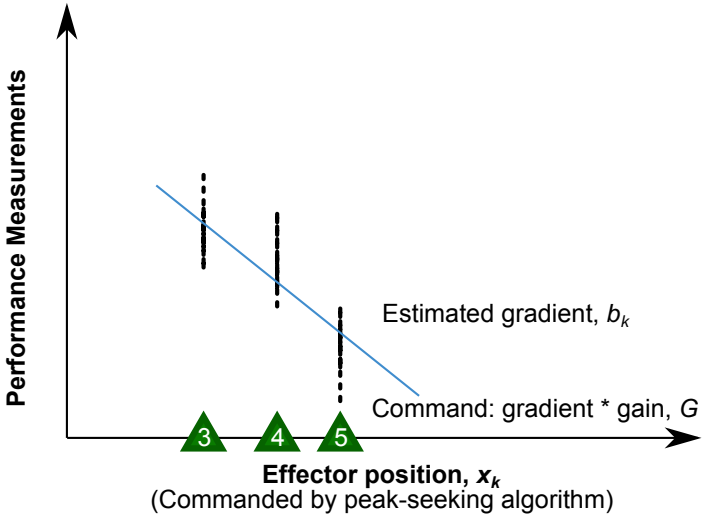

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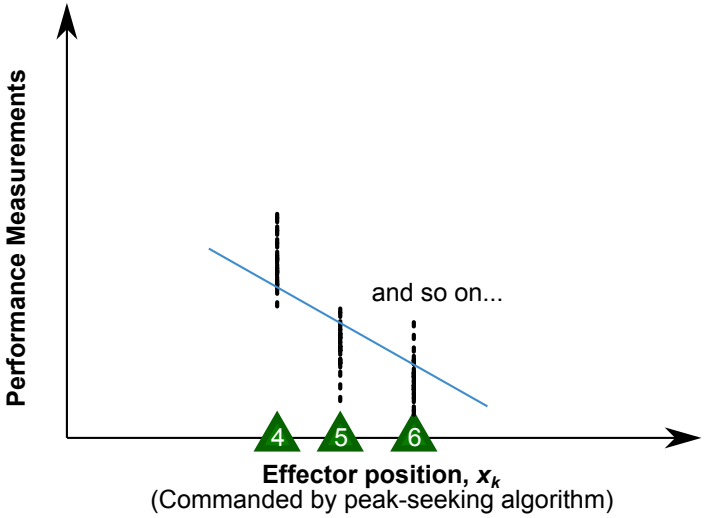
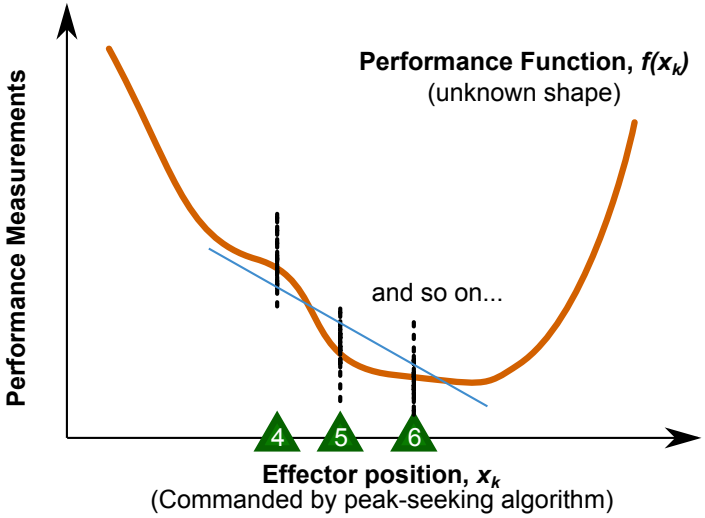
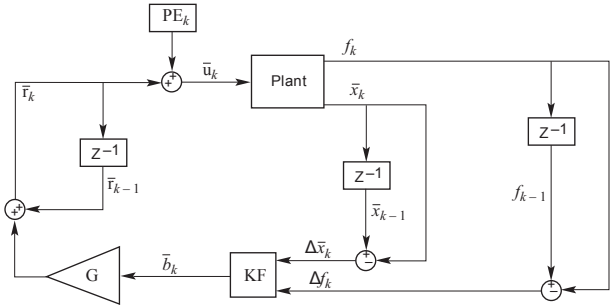


Peak-seeking algorithm, simplified example



Peak-seeking algorithm architecture

Peak-seeking algoritm architecture

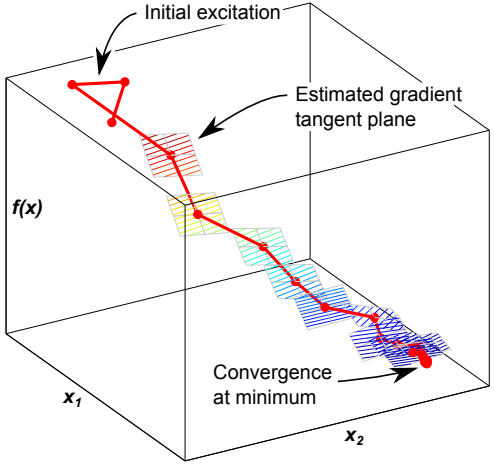


KF Time-varying Kalman filter

PE Persistent excitation

Plant Aircraft, NDI, & autopilot

Notional 2-effector example



Design parameter variations

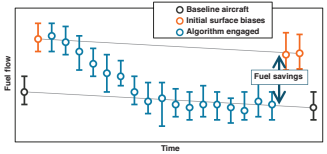
- G Gain applied to estimated gradient
- M Number of measurements for gradient estimate (3, 5, 7, & 10)
- N Number of independent effector groups controlled by algorithm
- f Performance measurement signal
  - Research fuel flow meters
  - Power lever angle (throttle position)
  - Production fuel flow meters
- Window Width of time-averaging window in seconds (10, 20, & 40)

Test parameter variations

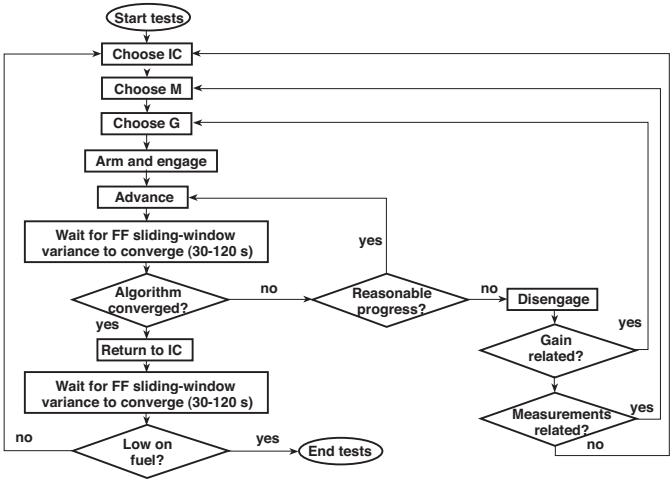
IC Initial configuration
- Production trim configuration (baseline)
- High-drag "corner" alternative trim configurations ▸ Initial trim sets

KCAS Knots calibrated airspeed
- 240 kn
- 200 kn

Flight-test technique

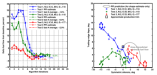
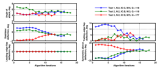
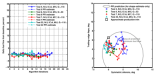
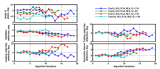
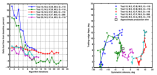
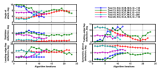
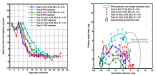
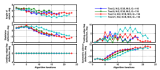


- Manual advance of algorithm iterations
- Control room "audibles" for pilot-selected mode
- Approximately 20 min per test point

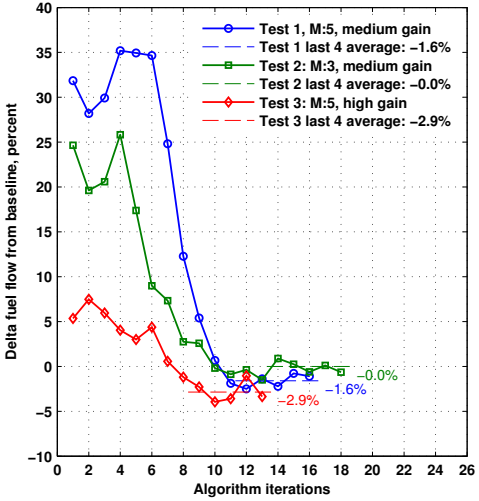


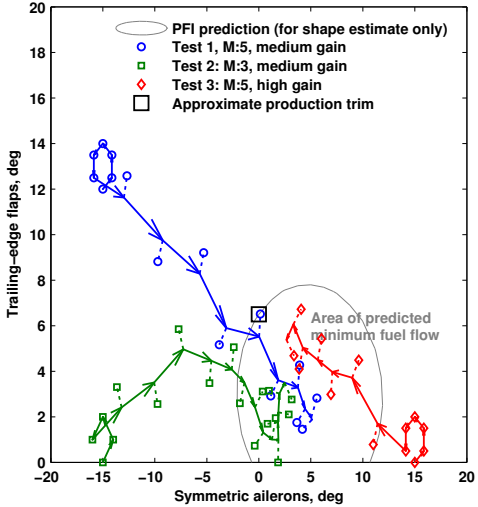
Selected test results

▸ Test configurations flown

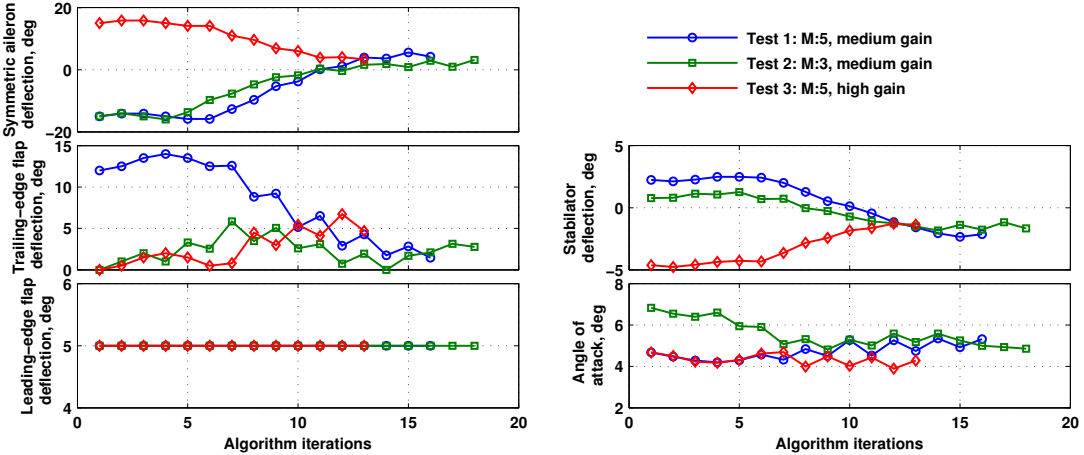
Comparison	Convergence	Surface positions
Nominal results		
Initial configuration A		
Varying flight condition		
Performance metrics		

Algorithm convergence - first three tests

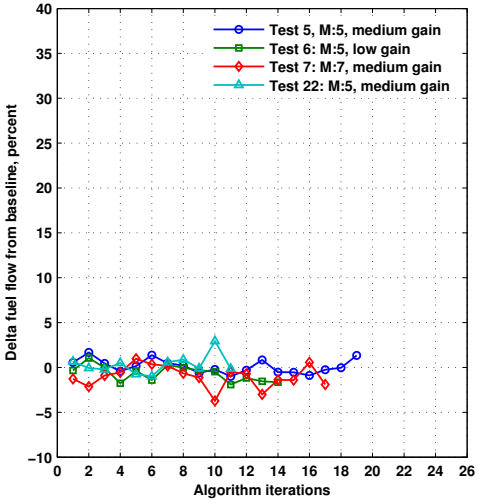


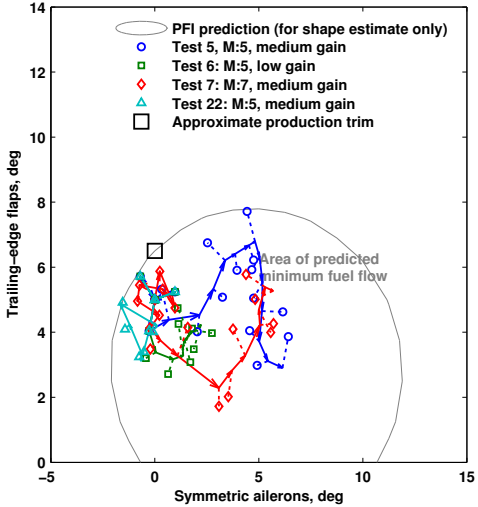


Surface positions - first three tests



Algorithm convergence - initial configuration set A





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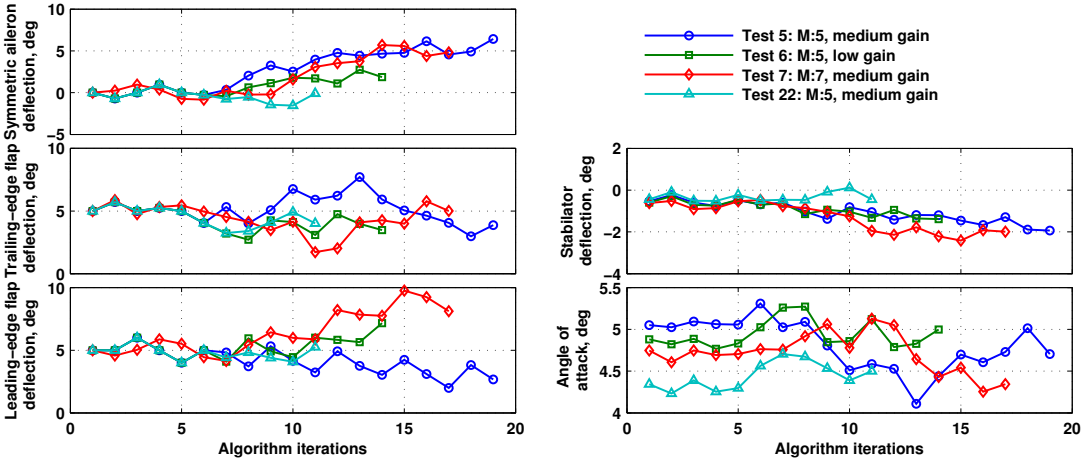
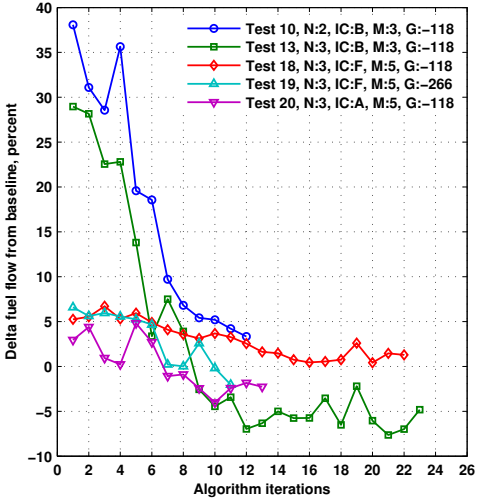
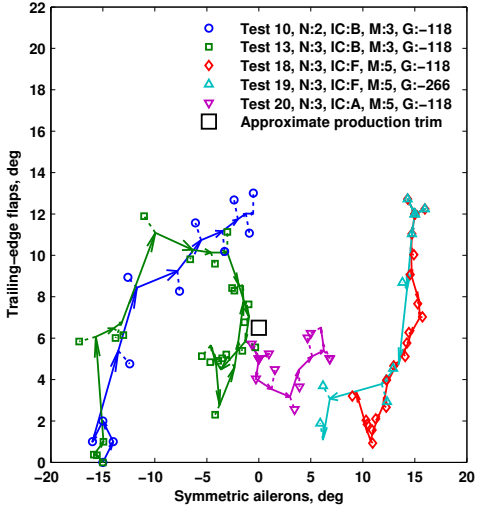


Algorithm convergence at 200 KCAS flight condition





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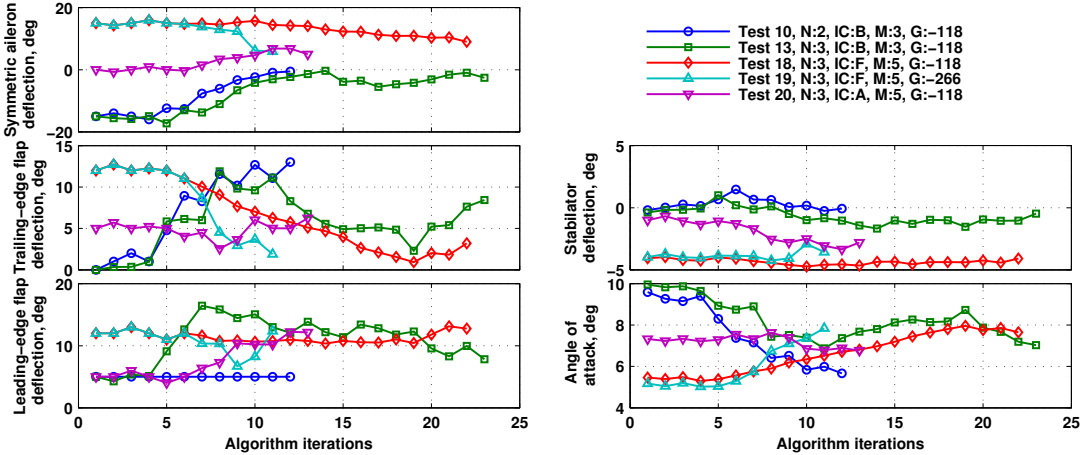
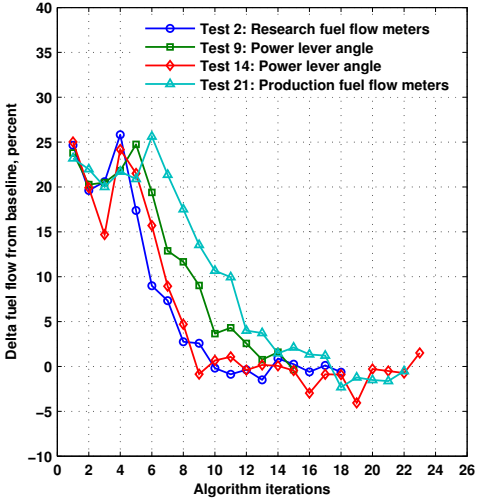
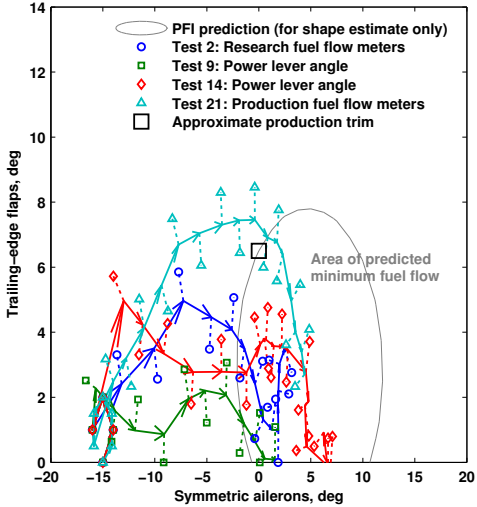
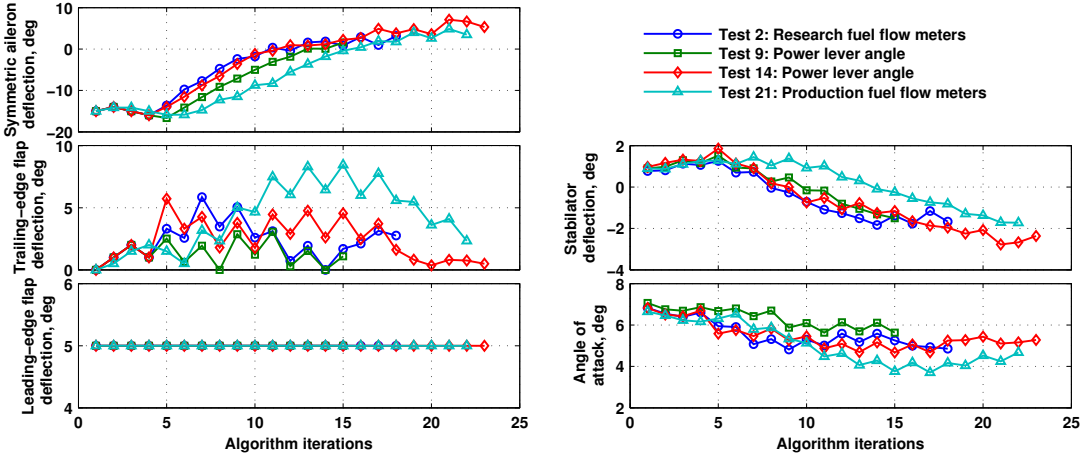


Algorithm convergence with various performance metrics





Surface positions with various performance metrics



Conclusions

Six research flights

- Algorithm consistently converged on low fuel flow trim configurations
- Trim setting found requiring approximately 3% less fuel flow vs baseline
- Fuel savings of 1% to 2% were more typical
- Research-grade fuel flow meters were not required
- Algorithm performed well at two flight conditions
- Pilots noted that algorithm did not impact ride quality

Future research

- Transport-class aircraft
- Aircraft with external stores
- Lateral-directional axes
- Supersonic regime, longitudinal lift distribution, wave drag
- Test algorithm in moderate turbulence
- Generate guidelines for implementation on other aircraft
- Increased automation
  - Advancement of algorithm
  - Disengage for maneuvering
  - Suspend iterations for turbulence

Questions/contact

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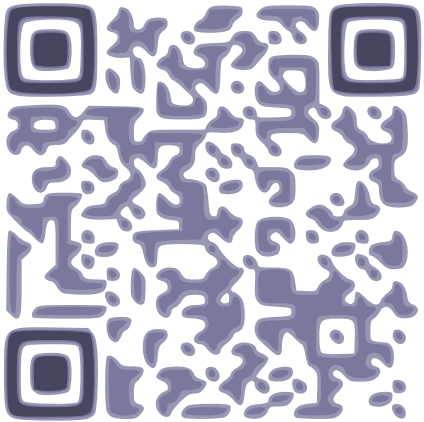


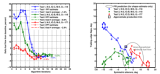
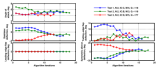
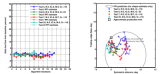
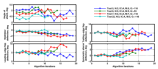
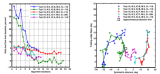
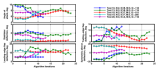
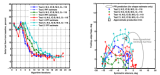
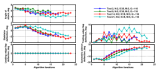
Test configurations flown

◂ Selected results

Test	Flight	KCAS	Performance function, f	IC set	N	Window, s	M	G
1	1	240	Research FF	C	2	20	5	-118
2	1	240	Research FF	B	2	20	3	-118
3	1	240	Research FF	D	2	20	5	-177
4	1	240	Research FF	F	3	20	5	-118
5	2	240	Research FF	A	3	20	5	-118
6	2	240	Research FF	A	3	20	5	-53
7	2	240	Research FF	A	3	20	7	-118
8	2	240	Research FF	E	3	20	5	-118
9	3	240	Power lever angle	B	2	20	3	-118
10	3	200	Research FF	B	2	20	3	-118
11	3	240	Research FF	A	3	10	10	-59
12	3	240	Research FF	A	3	40	3	-118
13	4	200	Research FF	B	3	20	3	-118
14	4	240	Power lever angle	B	2	20	3	-118
15	4	240	Research FF	A	3	10	10	-133
16	4	240	Research FF	A	3	20	10	-133
17	4	240	Research FF	A	3	40	3	-118
18	5	200	Research FF	F	3	40	5	-118
19	5	200	Research FF	F	3	40	5	-266
20	5	200	Research FF	A	3	20	5	-118
21	5	240	Production FF	B	2	40	5	-118
22	5	240	Research FF	A	3	40	5	-118

Selected test results

▸ Test configurations flown

Comparison	Test numbers	Convergence	Surface positions
Nominal results	1, 2, & 3		
Initial configuration A	5, 6, 7, & 22		
Varying flight condition	10, 13, 18, 19, & 20		
Performance metrics	2, 9, 14, & 21		

Flight conditions and initial trim sets

Flight conditions

- 25k ft MSL, 240 KCAS
- 25k ft MSL, 200 KCAS

Initial effector biases in degrees

Set	Ailerons	TEF	LEF
A	0	5	5
B	-15	0	5
C	-15	12	5
D	15	0	5
E	15	12	0
F	15	12	12

TEF Trailing-edge flaps

LEF Leading-edge flaps

Previous research: Real-time trim optimization

- Performance Seeking Control, F-15 (Orme et al.)
  - Stabilators
  - Variable cowlings
  - Inlet ramps
  - Nozzles
- Adaptive Performance Optimization, L-1011 (Gilyard et al.)
  - Symmetric ailerons
  - Model to estimate drag
  - Drag reduced by approximately 1%
- Extremum-seeking control, simulation studies (Krieger and Krstic)
  - Optimizing airspeed for best endurance
  - Atmospheric turbulence as only excitation

Previous research: Peak-seeking control

- Formation flight for fuel savings
  - Position in formation (Binetti et al.)
  - Position in formation (Ryan and Speyer)
  - Spanwise lift distribution (Hanson and Ryan)
- Trim optimization
  - Single effector group: X-48B simulation studies (Griffin et al.)
  - Three effector groups: F/A-18 simulation studies (Schaefer and Brown)[1]

[1] Companion paper